

Successful Operation of Farm-Based Anaerobic Digestion

▪ Key Items to Monitor and Why ▪

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February 2018

Introduction - Why Monitor

The primary goal of anaerobic digester monitoring is the establishment of system performance traits in order to **avoid upsets and failure**, while assuring reliable, efficient system operation with high levels of beneficial biogas (methane) generation. The discussions and recommendations provided in this document assume the most general, generic farm-based anaerobic digester operating situation where dairy operations are subject to change and changeable external organic feedstocks are accepted (co-digestion) potentially leading to system feed variations that could result in system struggles or upsets if proper monitoring and control were not provided.

Overview

From the simplest perspective, there are two fundamental synergistic microbial populations that are at the heart of the anaerobic digestion process. Knowledge of these two groups of microorganisms is most useful for understanding why monitoring any anaerobic digester (AD) greatly enhances the likelihood of steady, reliable and successful operation. From a simplified perspective, the first microbial population is the **acid producers** and the second is the **acid consumers**. Acid producers are a large, diverse, multiple specie community of rapidly responding acid producing microorganisms. The acid consuming microorganisms rely on those acids produced as their only food source in a typical digester. Since the acid producers have a higher capacity to generate acid faster than the acid consumers can consume it, monitoring is needed in many digesters to make sure the two microbial populations don't get out of balance. Digester pH and buffering capacity link these two relationships. From experience it has been found that robust methane activity is fundamentally limited to a pH range of between 6.5 and 8.2. Outside of this range acid consumption and methane production nearly stops. Importantly, the acid producers thrive at pH values less than 6.5, only slowing down when pH values as low as 4 to 5 are reached, thus they continue to produce acid after the acid consuming methane producers have substantially slowed or stopped their acid consumption. This can lead to acid accumulation, depletion of digester buffering capacity and potentially digester upset. It is worth noting that the practical operating pH range for dairy manure digesters is usually from 6.8 to 7.4, with many at 7.1 to 7.4.

Acid Production – Acid Consumption Balance

The key to digester stability is to maintain a balance between the rate at which acids are produced and consumed. The diverse microbiological population responsible for converting the complex manure feedstock to acids and the capacity of the methane generating population to keep up with that acid production as it consumes those acids must match. The complex interrelationships and many conversion pathways used by the myriad microbial communities responsible for digesting the materials fed, end with the simple production of volatile fatty acids (VFAs). These VFAs are the methane bacterial population's only food source for methane and carbon dioxide generation (normally). When off-farm substrates from simple, highly biodegradable, high energy materials such as whey or glycerin, or complex food waste mixtures of varying degrees of bioavailability are fed, vastly different rates of acid production result. The digester operator must account for these

relationships and adjust digester feed inputs accordingly in order to keep the microbial balance between acid production and acid consumption. When these communities' balance is maintained, stable digester performance and steady biogas production can be expected. One of the central goals of monitoring is to ensure this good performance.

It is essential for the digester operator to understand that the acid forming microbes are comparatively fast at the job compared to the relatively very slow acid consuming, methane producing bacteria.

The general characteristics of the acid producer community compared to the acid consuming methane producing community is key. Overall the many organisms responsible for converting the raw materials fed are substantially faster growing as a group and much quicker to respond to changes in the digester feed and operating conditions than the much slower methane producers. Methane producers are totally dependent on the acid generated by the acid producing community. The methane generators can only use the acids (VFAs) produced for their diet. However, if the acid is generated at a rate greater than it is consumed by the methane bacteria and converted to biogas (methane and carbon dioxide), acid concentrations in the digester will increase. This

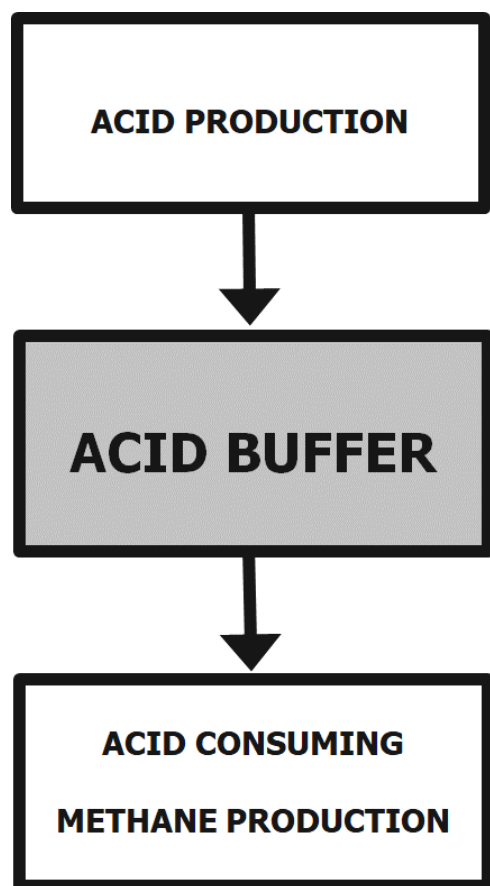


Figure 1. Pivotal role of acids and buffering in anaerobic digestion.

elevation of acid concentration can lead to the drop of overall pH. If unchecked such acid accumulation and decreasing pH can cause the methane community to stop all activity. As the methane bacteria slow down and perhaps eventually stop consuming the acid produced, the digester environment continues to become increasingly acidic until the acid formers essentially self-destruct (pH levels as low as 4 to 5 may be required for total acid producing community failure as discussed previously). This catastrophic total system failure is sometimes referred to as a stuck, sour or pickled digester. A condition to be avoided as it can take weeks to fully recover. It should be noted that such a system failure need not be persistent but is usually an episode of acute imbalance, not a chronic condition. Short-term low pH will not destroy either the acid producing or acid consuming bacterial communities. Most can recover once favorable digester conditions are reestablished. Adding alkalinity and buffering to the digester to obtain a favorable pH, and greatly lowering or stopping feed can allow the acid consumers to recover and biogas methane production to resume, thus reestablishing balance.

System Buffering

Fortunately the contents of any digester have the capacity to buffer (resist) acid production to some finite (limited) extent. This buffering capacity that allows for some accumulation of acids without appreciably affecting pH is the key factor linking acid production and acid consumption by the digester's two microbial communities.

The critical connection between these two communities is shown in Figure 1.

Due to the rapid response of the acid producers to any changes in the digester, any significant change in digester conditions from a shift in the raw feedstock added to the digester, to a change in the digester environment (pH, temperature, feed characteristics and rates), can cause these mutually dependent and normally mutually beneficial groups of microorganisms to create stressful conditions in which both can have their activity dramatically decreased. This can limit digester capacity and unchecked can lead to process failure requiring drastic measures in order to restart the digester.

On a whole, today's anaerobic digestion systems perform well. Their design and operation has greatly improved compared to many of the early systems. Though not always the case, a combination of poor management and weak design of early AD system installations resulted in repeated failure episodes for a majority of those operated and designed prior to 1998 (~ 65%). Even with current improved digester performance, failure and performance struggles can still occur. Inadequate operational management and poor process oversight of ADs operated by farm staff with no formal AD operation experience, little or no training, and whose digester operation and monitoring efforts are only a small portion of their daily farm related activities is the norm on most farms. This can often lead to on-going challenges for these systems.

Thankfully the acid concentrations present in a digester can vary considerably, over an appreciable operating range, while pH remains steady or within a good range for methane producers to thrive and thus the system remains in balance. This buffering capacity allows increased acid production to occur, with increased acid concentration in the digester without stressing the methanogens. Thus, though slower, the methane producing population growth rate will increase in response to the rise in acid (their food source) concentration, in turn more methane bacteria are produced, who then consume the excess acid that had accumulated and a new system balance is achieved. All this can occur without any stress on the total microbial system and no harmful pH drop. The key is to not exhaust the buffering capacity. Digester buffering capacity typically responds to increasing acid concentrations as shown in Figure 2. Please note that both the shape of the curve shown and the various operating pH values noted are examples only. Every operating anaerobic digester will have its own distinct operating state that with experience the operators can determine by proper monitoring.

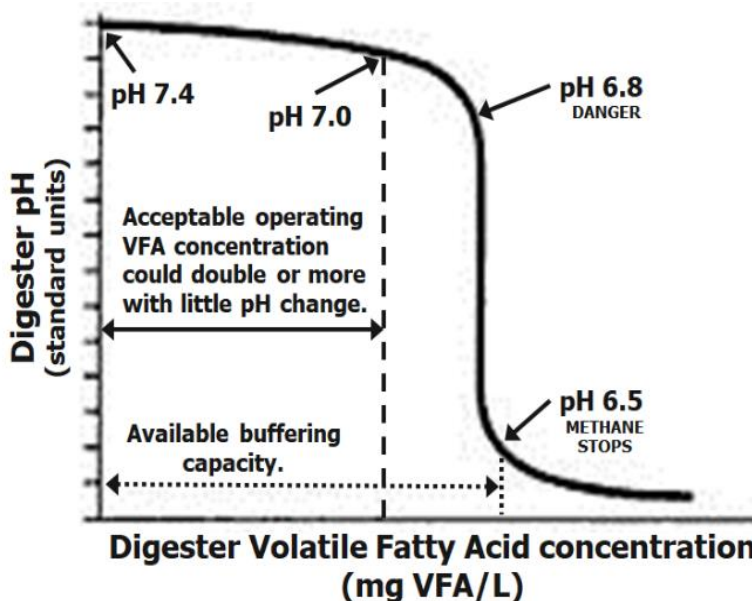


Figure 2. Simplified, hypothetical example showing the conceptual relationship between acid concentration and pH in typical anaerobic digesters.

The first and most critical aspect of the acid concentration - pH relationship is how little the pH changes during successful digestion. The left side of the curve in Figure 2 is nearly flat. This means that as VFA concentration increases little, or often almost no, drop in pH occurs. This can be true over a wide

typical digester range of from 50 to 500 mg VFA/L (or even higher in many cases, 500 to 1,000 mg VFA/L). The alkalinity (ALK) or buffering capacity present effectively neutralizes the extra acids initially present, allowing the acid consumption by the methane producing population to catch up with the acid increase and restore balance. Typical manure digester ALK ranges are in the neighborhood of from 2,000 to 5,000 mg Tot-ALK/L.

At some VFA concentration, the buffering capacity is exhausted. At that point very small increases in acid concentration causes dramatic decreases in pH, as depicted by the vertical drop shown. The ALK difference between the normal good operation pH range and a chosen end point, when methane generators are under stress or stop completely, represents the available buffering capacity of the system. The amount of VFA required to exhaust available buffering capacity between these two pHs is shown in Figure 2. By tracking this buffering capacity, the operator can detect a potential imbalance situation and make adjustments, typically days before the system is in trouble. As can be seen, if pH measurements alone were to be relied on, by the time pH starts to drop the operator may have little or no time to take corrective action to avert system upset.

Key Monitoring Resources

Rigorous detailing of how the monitoring parameters for total solids (TS), volatile solids (VS), volatile fatty acids (VFAs), alkalinity (ALK), ammonia nitrogen (NH₃-N), biogas composition (%CH₄, %CO₂), pH, and temperature can be quantified on-site using methods assembled by Labatut & Gooch (2012).

By monitoring digester VFA and ALK concentrations, and determining the buffering capacity of the system, the operator can usually respond in a timely manner to avoid upsets (a minimum monitoring frequency of once or twice during a system's HRT is recommended). Relationships between these parameters can also be used as guidance tools alerting the operator to potential problems (discussed below).

Monitoring Parameters for Digester Control

While there are no established absolute rules for prioritizing the parameters to monitor, the following guidance is provided for consideration. For simple systems fed only manure from a single dairy operation, the first four typical monitoring parameters in the list below are recommended (1 to 4) at a once or twice weekly frequency. As system size and feed complexity due to added co-digestion materials increases, the additional parameters and more frequent monitoring should be considered. For single consistent added co-digestion materials, monitor parameters 1 to 10. Additional monitoring will be required with increased system size, acceptance of variable codigestion feeds, and utilization of biogas produced for cogeneration, boilers, pipeline gas sales, etc.

Key Point:

Similar to feeding a dairy cow, anaerobic digesters perform well when they are provided a steady diet and maintained at constant temperature. There are many examples of dairy AD operations that are successful with very little or no monitoring. These systems are those serving a dairy facility that provides a very steady feed waste stream with minimal changes in feed volume, concentration, or solids characteristics. **Judgement** is always required to determine monitoring time, energy and resources that are appropriate for a given situation. With the advice of the AD system vendor, technical expertise and the operational experience of other farm installations, an appropriate monitoring level for a given facility may be determined.

The focus of all monitoring is to provide steady feed and assure that the digester process is in balance such that good performance results.

Typical Monitoring Parameters:

1) Feed Rate: Volume and mass feed rates need to be steady. Aim for an operating feed flow goal of $\pm 5\%$ of reactor volume per day if 20-day hydraulic retention time (HRT), and/or an equivalent mass loading at $\pm 5\%$ of the average daily pounds of biodegradable volatile solids, if a 30-day HRT a variation of $\pm 3.3\%$, etc.). Feed equal volumes 10 to 30 times per day to provide a steady total daily feed at variations of less than $\pm 5\%$ to 10% for both volume and mass using a running average over the operating HRT. In many instances, particularly for manure only systems with steady waste generation characteristics, flow and mass are roughly equivalent. When this is not the case attention should be paid to both flow and mass loading. Daily mass biodegradable VS loadings should also be in the same low variation range as cited for flow. This can be especially true when a significant portion of the total digester feed load is from non-manure, codigestion materials. The biodegradability of each feed source should also be carefully considered to assure steady mass loading (see volatile solids discussion and example calculations below).

2) System Equipment: Sensor feedback to assure that major equipment is functioning properly (pumps, mixers, etc.).

3) Total Solids (TS): Dry solids content of the material or slurry or liquid tested to assure steady feed rates. (See Labatut & Gooch, 2012)

4) Temperature: The rate of growth and digestion by the AD's biological community is directly related to temperature within typical operating ranges. Since the amount of biogas produced is of sufficient quantity to be used directly or indirectly as a source for heating and maintaining a digester at the optimum temperature (98°F to 100°F) for biogas production, it is typically used to increase the rate of digestion and decrease the system's overall treatment volume and therefore capital cost. The resulting comparatively smaller digester volume required lowers construction cost more than compensating for the added cost of the heating components. This generally holds true even in cold climates. At the typical operating range 98°F to 100°F; a temperature change of more than 3°F to 4°F over a period of 10 days or less can lead to an imbalance between the rapidly responding acid forming bacteria and the slower methane producing community and is to be avoided. (See Labatut & Gooch, 2012)

5) Volatile Solids (VS): For VS measurement protocols see Labatut & Gooch, 2012.

Volatile solids consumption, conversion and resulting biogas generation by anaerobic digester biological communities is at the heart of a smoothly functioning digester. For manure-only digesters VS destruction is in the range of 30-42% (Gooch et al., 2011). In systems co-digesting manure and additional off-farm feedstocks, the percent VS destruction of the waste is typically higher, but its magnitude varies according to the bioavailability of the co-digestion wastes fed. The fact that a potential feed is 100% VS (or nearly so) does not inform how the material behaves in an AD. The biodegradability of the VS fed can be very important.

To understand the importance of VS biodegradability consider the following. Both pecan shells and table sugar are near 100% VS. However, the pecan shells are almost entirely non-biodegradable and are not typically converted to acid, then to biogas in an AD, while the sugar would be rapidly processed. Thus, the biodegradable characteristics of VS fed determines the response of the AD microbial community, rapid or slow acid production, biogas methane generation and ultimately the requirements for steady operation.

As an example, the biodegradability of each feed component may be dramatically different and should be taken into consideration. When assessing biodegradability, literature values should not be relied on (nor the following examples) but it is highly recommended that each type of waste feed to be accepted and loaded into the AD be tested for each farm's operation. Some typical biodegradability values presented in Figure 3 may be used to consider some feed scenario examples only. ***Again this figure nor other literature values are not to be relied upon as they may not reliably characterize a given farm system's actual operation.***

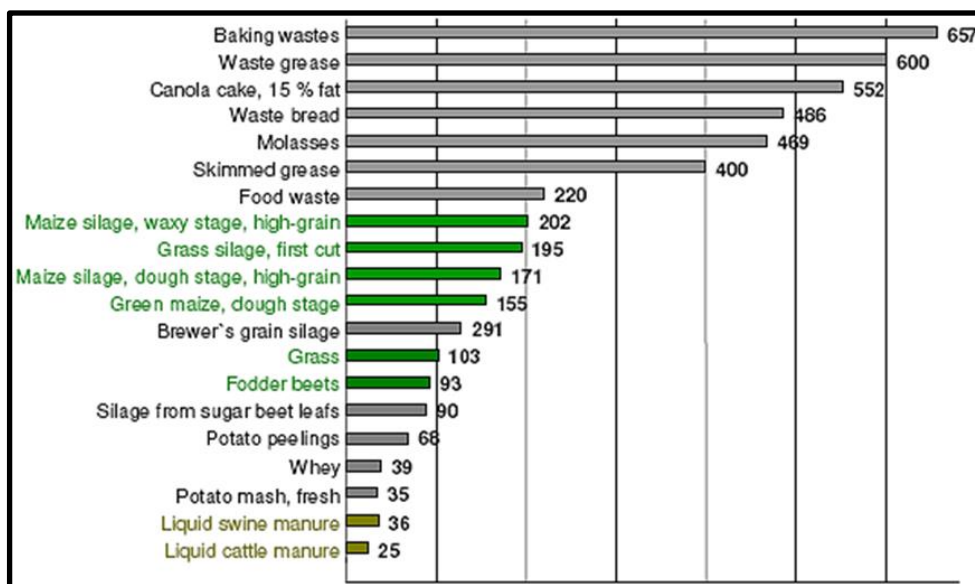


Figure 3. Values represent biogas volume units produced per VS mass units destroyed or relative bioavailable energy expressed as biogas production (Mathias Effenberger, 2006).

A typical example scenario to consider would be if 300 lb VS/day of manure was the feed goal and up to 1/3rd of the total load is to be off-farm codigestion feed. Note that each pound of manure VS equals 1.0 of lb VS_{manure} or manure volatile solids equivalent by definition.

From Figure 3 it may be seen that the biodegradable energy in whey is about 1.6 times that of the VS in liquid cattle manure. The increased biodegradability factor (*bf*) is determined by taking the value of 39 for whey and dividing it by the reference (or baseline) value of 25 for manure.

Biogas biodegradability units for whey = 39; biogas biodegradability units for manure = 25;

Therefore the equivalent manure volatile solids mass (VS_{manure}) loading per pound of whey:

$$VS_{\text{whey}} \times bf = VS_{\text{whey}} \times (39/25) = 1.6 VS_{\text{manure}} \text{ as whey}$$

Thus a pound of whey VS fed to an AD is equivalent to feeding 1.6 pounds of manure VS.

Consider two illustrative examples:

Example 1

Take the example digester feed of 300 lbs. VS/d at 1/3rd off-farm codigestion whey and 2/3rd manure, the equivalent VS_{manure} loading may be calculated as:

$$\begin{aligned} & [(100 \text{ lbs. VS}_{\text{whey}}) \times (1.6 \text{ VS}_{\text{manure}}/\text{VS}_{\text{whey}})] + [(200 \text{ lbs. VS}_{\text{manure}}) \times (1.0 \text{ VS}_{\text{manure}}/\text{VS}_{\text{manure}})] = \\ & = [160 \text{ lbs. VS}_{\text{manure as whey}}] + [200 \text{ lbs. VS}_{\text{manure}}] = 360 \text{ lbs. VS}_{\text{manure}} \end{aligned}$$

If a 20-day HRT digester was being operated steadily at a straight manure loading of 300 lbs. manure VS per day and it is desired to adopt the example codigestion feed scenario, this would represent an equivalent VS_{manure} increase of 360/300 or 1.20 or 20% increase. A maximum daily mass load increase of 5% guideline means that the load should be gradually increased over a minimum of four days from the initial 300 lbs. VS_{manure} loading to the new 360 lbs. VS_{manure} load level.

Example 2

A second more extreme example scenario would be if it were desired to load 1/3rd of the daily mass as restaurant waste fat, oil and grease (FOG).

Biogas biodegradability units for FOG = 600; biogas biodegradability units for manure = 25;

Therefore the equivalent manure volatile solids mass (VS_{manure}) loading per pound of grease (FOG):

$$\text{VS}_{\text{FOG}} \times bf = \text{VS}_{\text{FOG}} \times (600/25) = 24 \text{ VS}_{\text{manure as FOG}}$$

Thus a pound of waste grease (FOG) VS fed to an AD is equivalent to feeding 24 pounds of manure VS.

So for the example digester feed scenario of 300 VS lb/d at 1/3rd off-farm codigestion FOG and 2/3rd manure, the equivalent VS_{manure} loading may be calculated as:

$$\begin{aligned} & [(100 \text{ lbs. VS}_{\text{FOG}}) \times (24 \text{ VS}_{\text{manure}}/\text{VS}_{\text{FOG}})] + [(200 \text{ lbs. VS}_{\text{manure}}) \times (1.0 \text{ VS}_{\text{manure}}/\text{VS}_{\text{manure}})] = \\ & = [2,400 \text{ lbs. VS}_{\text{manure as FOG}}] + [200 \text{ lbs. VS}_{\text{manure}}] = 2,600 \text{ lbs. VS}_{\text{manure}} \end{aligned}$$

If a digester was being operated steadily at a straight manure loading of 300 lbs. manure VS per day and it is desired to adopt the second example codigestion feed scenario, this would represent an equivalent VS_{manure} increase of 2,600/300 or 8.7 or 770% increase. Assuming a digester HRT of 20 days, a maximum daily mass load increase of 5% guideline means that the load should be gradually increased over a minimum of 154 days from the initial 300 lbs. VS_{manure} loading to the new 2,600 lbs. VS_{manure} load level. Clearly if a digester were to suddenly switch from whey to FOG as described by these two example scenarios, **a disastrous overload would occur!**

One additional important note on the addition and control of VS mass loading to an AD; the non-manure material being brought in from off-farm should **not** be added straight to the influent of a

plug flow AD but rather be blended, and thoroughly mixed with the manure feed stream to produce a homogeneous digester feed throughout the operating day. It is also recommended for complete mix digesters as well, but it is not such a stringent or absolute requirement for the complete mix digester configuration.

It should be noted that the amount of inerts or fixed solids in a waste stream is the difference between TS & VS. It is these non-digestible solids that can accumulate over time in the bottom or top of a digester therefore effectively reducing the HRT. Knowing the rate of accumulation of fixed solids is important so required adjustments to the loading calculations can be made (for the case with high loading rate digesters) and scheduling of vessel clean out can be set.

6) Volatile Fatty Acids (VFA): It is recommended that testing be performed a minimum of once or twice per HRT. Test regularly to detect rising or alarming levels of digester VFAs, keeping in mind that once pH levels start to drop, the system is already in serious trouble. (See Figure 2, discussion above and Labatut & Gooch, 2012.)

7) Alkalinity (ALK): Again, it is recommended that testing be performed a minimum of once or twice per HRT to detect falling or alarmingly low ALK levels, keeping in mind that once pH levels start to drop the system is already in serious trouble. (See Figure 2, discussion above and Labatut & Gooch, 2012.)

8) Recommended Key Alkalinity & Volatile Fatty Acid relationships to monitor:

a) VFA/ALK Ratio:

Ratio of the concentration of VFAs to ALK: mg VFA/L to mg ALK/L or VFA/ALK. Target value for VFA/ALK = 0.10 to 0.35, low end recommended. (See Metcalf & Eddy, 2014; and Speece, R., 2008.)

b) Reserve Buffering Capacity: Determine reserve buffering capacity or alkalinity available for pH neutralization as follows (See Speece, R., 2008):

- 1) Set a lower pH limit (~6.5 or perhaps a bit higher) that prevents serious upsets and/or represents a low pH risk level acceptable to your operation.
- 2) Every one to two weeks perform an acid addition test or titration of digester contents with acetic acid down to your chosen lower limit pH set point to determine the amount of acid required and thus the ALK available in the digester before buffering capacity is exhausted (see Figure 2 and discussion above).

Increased testing frequency should be considered for more heavily loaded systems, or digesters that receive multiple or varying quantities of off-farm co-digestion materials as feed to the system.

9) pH: A general indicator of digester health but not a good parameter to monitor for process control or to prevent upsets. Typically manure digester operation is around pH 7.0 ± 0.2 . Remember from the previous discussions that once pH starts to move the system has likely already entered a failure mode (See Labatut & Gooch, 2012).

10) Biogas production: Digester biogas (flow and composition) should be measured at least weekly and tracked. While being an important indicator of digester health, changes noted in biogas production and composition usually occurs well after the other more sensitive indicators

of system health have responded (as priority listed above). Typical manure digesters have a methane content of 58 to 65%. A drop in methane content over time indicates stress and potential problems. (See Labatut & Gooch, 2012)

11) Total Ammonia Nitrogen: Total ammonia-nitrogen (TAN) or ammonia is produced during the digestion of proteins in manure and other materials fed to manure digesters. Unionized ammonia or ammonia dissolved in the liquid AD contents can inhibit the digestion process and decrease its overall performance. This is dissolved gas in the digesting liquid, not ammonia generated in the biogas produced. Concentrations over 1,500 mg/L of ammonia-N in the liquid phase have been reported to be inhibitory for the digestion process at high pH (i.e., > 7.4); however, acclimation to higher ammonia levels (>5,000 mg/L) has been also reported in manure systems. (See Labatut & Gooch, 2012)

Sampling/ Monitoring Locations: Sampling and monitoring points are important. For general reactor monitoring the digester bulk contents are the most important. For plug flow systems, at least two monitoring points are recommended: a) digester input as fed after mixing, and b) near or in the effluent discharge. In the case of plug flow digesters that provide a recycle flow, additional monitoring within the vessel's first ¼ of the longitudinal length or in the mixing zone where any recycle is being introduced should be considered (reactor designer or vendor recommendations are best). In the case of complete mix digesters, monitoring is recommended within the mixed reactor contents near or within the effluent discharge point. For measures of efficiency and overall performance of any digester configuration, additional monitoring of the digester feed is recommended. Often AD systems will not have ready access to recommended sampling locations such that modifications should be considered to allow accurate monitoring.

Additional Monitoring Parameters:

For the average or typical operation, additional monitoring is not normally or routinely needed. As the system size, complexity and operating costs increase, the operator may be compelled to consider further monitoring. For these larger/or more sophisticated systems, the increased monitoring cost can readily pay for itself in most cases. In addition, certain system challenges are not addressed by the more usual or normal parameters. Thus, in some cases the monitoring, as listed below, may be beneficially considered.

- Toxicity (ammonia, chromium, copper, zinc, nickel, plus others)
- Gas pressure (manometer or gauge, taps at multiple locations)
- Cogeneration System, (power output, heat, combustion gases, engine oil, etc.)
- Foam levels
- Flare function
- Solids accumulation in digester bottom and / or floating mass on the surface (<10% of depth, <5% recommended)

Integrated System Awareness: Be aware of all significant operating conditions on the farm and with any codigestion materials received. Weather, equipment problems, dairy operational changes (ration or bedding change), feed variation in type or quantity (especially if the biodegradability is significantly different from the previous manure / codigestion mix), spills or other accidental additions to waste fed, presence of sanitizer toxics (foot baths) or other anti-bacterial materials, etc.

It is recommended that as a vital part of new system installation deliverables, a comprehensive, detailed, easy to use operations and maintenance manual should be included. The creation of this crucial document is recommended whether the project is directed totally by the farm, or is executed as a complete turn-key project by an outside consultant or technology provider (vendor). If an existing system does not have an appropriate operations and maintenance manual, it is highly recommended that the farm should seriously consider developing one either with farm resources or by obtaining the assistance of outside expertise. At the least it is recommended that an easy to use set of standard operating procedures (SOPs) be written covering the basics of routine digester operation.

Recommended Reading/References Cited

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